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Bench Top Interferometric Test Bed for LISA

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Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA

ABSTRACT

The optical paths on the LISA bench must have a length instability of less than 10 pm/$\sqrt{\text{Hz}}$ over time scales of 1 s to 1000 s. A small rigid interferometer has been constructed to measure the optical path length changes using various bonding techniques. The interferometer was constructed entirely from ultra-low expansion (ULE) glass by optically contacting ULE beamsplitters to a ULE bench. Preliminary results taken with the interferometer operating in air indicate optical path length fluctuations of approximately 100 pm/$\sqrt{\text{Hz}}$ or less for frequencies between 1 mHz and 1 Hz.

Keywords: LISA optical bench, optical contacting, heterodyne interferometer

1. INTRODUCTION

The present sensitivity goal of the LISA interferometer[1] calls for a displacement resolution of 40 pm/$\sqrt{\text{Hz}}$ between 1 mHz and 1 Hz. To achieve this level of performance optical path length fluctuations of the beams on the LISA benches should be kept to less than 10 pm/$\sqrt{\text{Hz}}$. Such path length fluctuations could be caused by bulk expansion of the bench and optics materials, and from motion in the bonds between the optics and the bench. The characterization of the latter noise source is the focus of the work presented here.

The LISA optics and optical bench are to be constructed from ultra-low expansion titanium silicate glass (ULE). ULE's low coefficient of thermal expansion[2] of 0 ± 30 ppb/K makes it a very attractive material for LISA. Several techniques are under consideration for bonding the beamsplitters and mirrors to the optical bench including optical contacting and hydroxy-catalysis bonding.[3] This paper outlines the design and construction of an interferometer used to evaluate the dimensional stability of optical contacting.

2. RIGID INTERFEROMETER DESIGN AND READOUT SYSTEM

A small rigid interferometer was constructed by optically contacting four ULE beamsplitters to a ULE bench. A conceptual layout of the interferometer is shown in Figure 1. A heterodyne readout system was implemented allowing the relative positions of the beamsplitters to be inferred from the phases of the beat notes measured at the interferometer outputs. The rigid interferometer is actually composed of two separate interferometers. Individually each interferometer output is sensitive to laser frequency fluctuations, rf local oscillator fluctuations and changes in the optical paths of the input beams. However, these noise sources are common to both interferometer readouts and thus are cancelled when the signals from the two interferometers are subtracted. Two ensure a high degree of noise cancellation the arm lengths of the interferometer must be matched as closely as possible.

Each beam is split into two beams and traverses one of the arm lengths of the interferometer before being combined with the other beam on two separate beamsplitters. The interference at the beamsplitter ports is detected by four photodetectors whose outputs are proportional to the detected optical power, P_N, P_S, P_E, P_W. For notational simplicity all electric field amplitudes, E_j, are real and are expressed in units of $\sqrt{\text{Watts}}$

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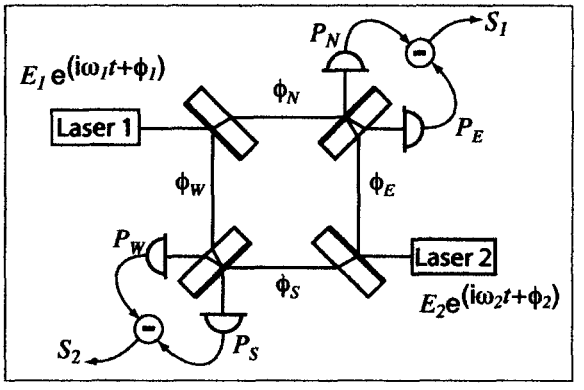

Figure 1. Conceptual layout of the rigid interferometer. The optical phase shifts for the various path lengths are indicated.

such that optical power is equal to E_j^2. Assuming all beamsplitters have a 50:50 splitting ratio the detected powers will be.

$$P_N = \frac{E_1^2}{4} + \frac{E_2^2}{4} + \frac{E_1 E_2}{2}\cos((\omega_1-\omega_2)t + \phi_1 - \phi_2 + \phi_N - \phi_E) \quad (1)$$

$$P_E = \frac{E_1^2}{4} + \frac{E_2^2}{4} - \frac{E_1 E_2}{2}\cos((\omega_1-\omega_2)t + \phi_1 - \phi_2 + \phi_N - \phi_E) \quad (2)$$

$$P_S = \frac{E_1^2}{4} + \frac{E_2^2}{4} + \frac{E_1 E_2}{2}\cos((\omega_1-\omega_2)t + \phi_1 - \phi_2 + \phi_W - \phi_S) \quad (3)$$

$$P_W = \frac{E_1^2}{4} + \frac{E_2^2}{4} - \frac{E_1 E_2}{2}\cos((\omega_1-\omega_2)t + \phi_1 - \phi_2 + \phi_W - \phi_S) \quad (4)$$

where the subscript denotes the North, East, South or West position as indicated in Figure 1 for the photodetectors and optical phase shifts. The laser frequencies are ω_1 and ω_2 and ϕ_1 and ϕ_2 are the total phase fluctuations of the fields at the interferometer inputs. The signals from adjacent photodetectors are combined with a subtraction to give S_1 and S_2. This eliminates excess intensity noise and enhances the interference signal.

$$S_1 = P_N - P_E = E_1 E_2 \cos((\omega_1-\omega_2)t + \phi_1 - \phi_2 + \phi_N - \phi_E) \quad (5)$$

$$S_2 = P_W - P_S = E_1 E_2 \cos((\omega_1-\omega_2)t + \phi_1 - \phi_2 + \phi_W - \phi_S) \quad (6)$$

The phases of these signals, $\angle S_1$ and $\angle S_2$, contain the laser frequency fluctuations, input phase fluctuations and phase shifts due to the interferometer optical paths. Measuring the difference between these phases cancels the common mode noise in the final output. The phase difference is proportional to the difference in arm lengths:

$$\Delta\Phi = \angle S_1 - \angle S_2 = \phi_N + \phi_S - (\phi_W + \phi_E) \quad (7)$$

As $\Delta\Phi$ is proportional only to the difference between the North-South and East-West beamsplitter separations this output is also insensitive to isotropic thermal expansion of the ULE bench when the interferometer has matched arm lengths. The change in relative separation of the beamsplitters can be inferred from this phase difference by multiplying $\Delta\Phi$ by $\lambda/(2\pi)$.

3. THE EXPERIMENT

The experimental layout is shown in Figure 2. The two interferometer inputs are derived from a 1 mW 633 nm Helium-Neon laser (Melles Griot 05-STP-901) operated in the frequency stabilized mode. The output of the laser is divided into two beams that are upshifted 40.000 MHz and 40.003 MHz by acousto-optic modulators (IntraAction AOM-40). This gives a heterodyne beat frequency at 3 kHz. Each beam is coupled into a

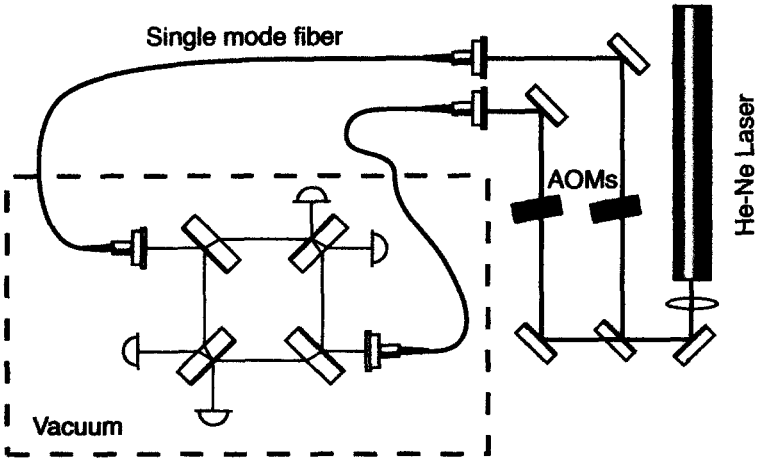

Figure 2. Simplified experimental layout. Dashed line indicates the vacuum chamber to be used for future measurements.

polarization maintaining fiber for spatial mode filtering. Eventually the measurement will performed in a vacuum chamber (currently the interferometer is operated in air). The outputs of the two fibers are then collimated and aligned into the interferometer using steering mirrors. The four interferometer output beams are aligned and focused onto photodetectors (Thorlabs PDA55) before the relevant electronic signals are subtracted using two low noise pre-amplifiers (Stanford Research Systems SR560). The outputs of the amplifiers are fed into a phasemeter[4] with a phase noise floor of less than 10^{-6} cycles/$\sqrt{\text{Hz}}$, corresponding to a displacement noise floor of less than 1 pm/$\sqrt{\text{Hz}}$ from 1 mHz to 1 Hz.

3.1. Optical contacting and interferometer alignment

The beamsplitter substrates with dielectric coatings were provided by CVI Laser and were specified to each have a bottom surface with $\lambda/4$ flatness at an angle of $90^\circ \pm 1'$ to the front optical surface. The perpendicularity of these surfaces is critical to the vertical alignment of the interferometer.

Although it is possible to align the input beams to ensure correct alignment of one of the interferometer outputs the second output can only be aligned using the interferometer beamsplitters themselves. The first three beamsplitters (NW, NE and SE) were optically contacted in approximately the correct positions as determined by a visual inspection. The input beams were then aligned using steering mirrors to give maximum fringe visibility on the North and East photodetectors. Adjustment of the position and orientation of the fourth beamsplitter are enough to completely align the remaining interferometer outputs, as measured by the South and West photodetectors.

Vertical alignment was completely dependent on the perpendicularity of the beamsplitters and the flatness of the ULE bench. Initially very low fringe visibilities were obtained (7%) due to poor vertical alignment of the interferometer. Detailed measurements of the vertical angles of 10 beamsplitters allowed selection of appropriately-angled beamsplitters. After exchanging and realigning the beamsplitters the fringe visibility increased to greater than 65% on all four outputs simultaneously.

The optical contacting itself posed no problem as long as the optics and bench were sufficiently clean. Immediately before contacting both the bench and beamsplitters were thoroughly cleaned using Lens Clens no. 3 cleaning fluid for uncoated optics. One of the main difficulties encountered with the interferometer construction was optically contacting the fourth beamsplitter in the correct position. In general, once the beamsplitter had contacted to the ULE bench no further alignment was possible. However, it was realized that after placing a drop of cleaning fluid on the ULE bench adjacent to a previously contacted beamsplitter the fluid was absorbed into the bond interface. The beamsplitter could now be freely moved around without losing contact with the bench. Over a period of a few minutes the cleaning fluid evaporated and the beamsplitter

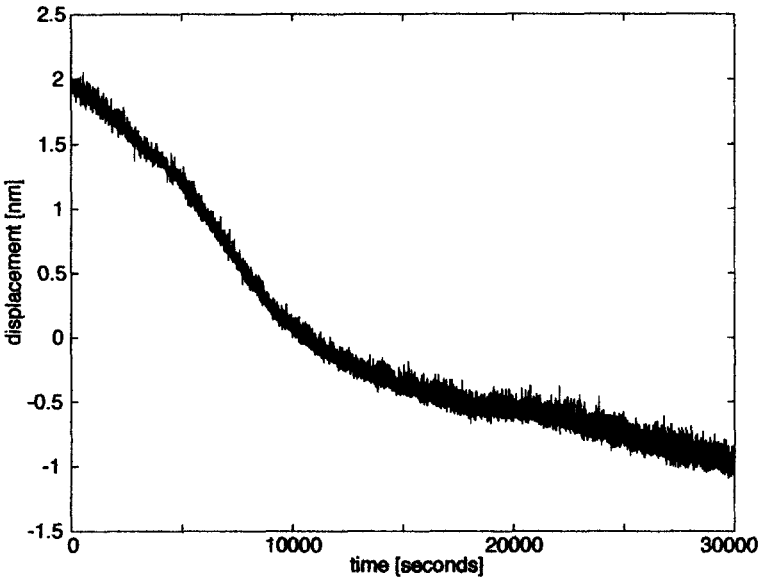

Figure 3. Measured mirror position over 30,000 s. Each measurement point is the result of 0.5 seconds of averaging.

gradually became harder to move until eventually it was rigidly contacted in place once again. This allowed the fourth beamsplitter to be aligned and the fringe visibility to be maximized. Note that in order to obtain a strong bond it was necessary to apply a small amount of pressure during the cleaning fluid evaporation. The bonds achieved by application of the cleaning fluid in many cases seemed stronger and more complete than the original bonds. Moreover, this alignment process could be repeated several times if necessary by re-adding fluid until the satisfactory alignment was achieved. Using this technique it was possible to align the interferometer almost perfectly in the horizontal dimension with the residual vertical misalignment limiting the fringe visibility to 65%.

4. RESULTS

For the results presented below the optically contacted ULE interferometer was operated in an ordinary atmospheric environment inside a class 100,000 clean room. A box was placed over the ULE interferometer to minimize air currents. Figure 3 shows the measured displacement over a 30,000 s period. Each data point represents the phase difference averaged for 0.5 s.

The data of Figure 3 exhibits a long term drift of nearly 3 nm over the 30,000 second run. The cause of this drift is currently unknown. Simultaneous measurements of the temperature of the ULE interferometer showed no correlation with the interferometer results. The laser frequency fluctuations were also considered although with an arm length mismatch of less than 1 mm this is an unlikely noise source. A frequency shift of more than 450 MHz would be required to account for the measured 3 nm change. Tests of the photodetection and phasemeter electronics were ruled out as the phase difference between the North and East photodetectors was measured to much better than this level over similar time scales. The most likely cause of the long term drift is misalignment of the input beams due to relaxation of the input beams' steering mirror mounts. This effect, which is normally of second order, was significant due to the imperfect initial alignment of the interferometer. For example, $\Delta\Phi$ could be varied by several degrees by adjusting the vertical alignment of the input beams.

The root power spectral density of this data is shown in Figure 4. The spectral density is at or below 100 pm/$\sqrt{\text{Hz}}$ for frequency between 1 mHz and 1 Hz. Although this is a factor of 10 above LISA requirements the results are encouraging when it is considered that the interferometer is operating in air. Note that the

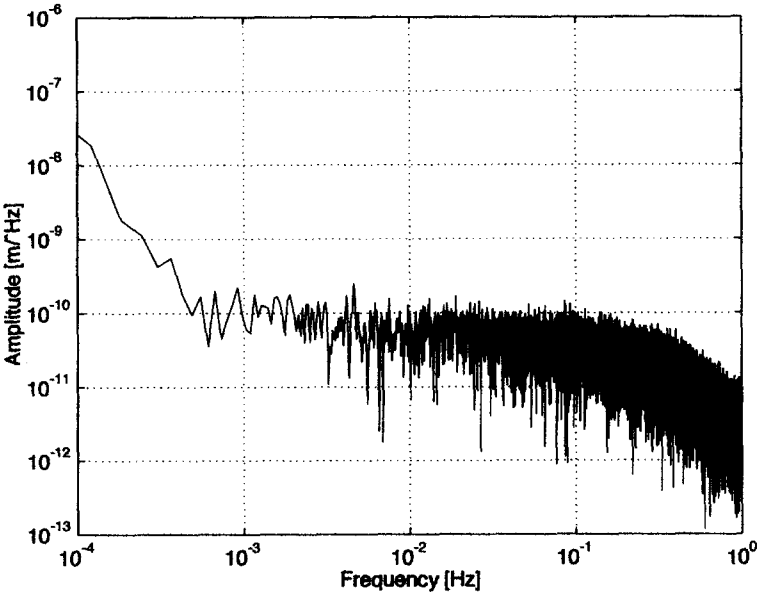

Figure 4. Root power spectral density of the differential beamsplitter motion.

spectral density is flat for frequencies down to below 1 mHz and the long term drift appears as 1/f noise below about 0.5 mHz.

5. CONCLUSION

We have constructed a rigid interferometer entirely of ULE using optical contacting. Preliminary results taken with the interferometer operating in air using a heterodyne readout system show differential path length fluctuations of approximately 100 pm/$\sqrt{\text{Hz}}$ or less over time scales of 1 to 1000 seconds. This performance is approximately a factor of 10 away from meeting the LISA specifications. Future tests will be performed with the interferometer operating in vacuum.

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REFERENCES

1. LISA science team *LISA pre-phase A report*, Addison-Wesley, Reading, Mass., 1994.
2. ULE Corning Code 7972 Ultra Low Expansion Glass data sheet.
   `http://www.corning.com/semiconductormaterials/pdf/ule_2_page_spec_sheets.pdf`
3. O. Jennrich, P. McNamara, D. Robertson, S. Rowan, H. Ward and J. Hough, "Interferometry developments for LISA and SMART-2," *Class. Quantum Grav.* **19**, pp. 1731–1737, 2002.
4. D. A. Shaddock "Digital Phasemeter Using Undersampling Demodulation" *in preparation*, 2002.